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Soliton evolution and control in a two-mode fiber with two-photon absorption

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Soliton dynamics are numerically investigated in a two-mode fiber with the two-photon absorption, and the effects of the two-photon absorption on the soliton propagation and interaction are demonstrated in different dispersion regimes. Soliton dynamics depend strictly on the sign and magnitude of the group velocity dispersion (GVD) coefficient of each mode and the strength (coefficient) of the two-photon absorption. The two-photon absorption leads to the soliton collapse, enhances the neighboring soliton interaction in both modes, and increases the energy exchange between the two modes. Finally, an available control is proposed to suppress the effects by the use of the nonlinear gain with filter.

Keywords: soliton, two-mode fiber, two-photon absorption, nonlinear gain, filter

PACS: 42.65.Tg, 42.79.Gn, 78.40.–q **DOI:** 10.1088/1674-1056/ab5784

1. Introduction

It is well known that optical soliton is based on counterbalancing of the group-velocity dispersion and the nonlinear refractive index of the optical fiber. Optical soliton properties (such as shape, height, and width) can be maintained when the soliton propagates over thousands of kilometers by the use of optical amplifiers, and optical soliton communication now has an impact on the communication.[1,2]

The design of the soliton communication systems requires consideration of several factors, such as the soliton properties (such as shape, height, and width), the soliton separation, and the distance between successive amplification stages. Meanwhile, there are many perturbations (such as high-order nonlinearity) which need to be considered in a practical soliton system, they lead to the fluctuation in the amplitude or pulse-width of the soliton, and deform the soliton shape. Their effects can not be neglected on the characteristics of the soliton system, such as degrading the stability of the coherently amplified solitons, increasing the time jitters in arrival, and reducing the signal-noise-ratio of the soliton communication.[3,4]

Mode-division multiplexing (MDM) systems based on the multimode fibers (such as a two-mode fiber of LP_{11} and LP_{01} modes) have been proposed as a promising technology to increase the transmission capacity of optical fibers, and have attracted worldwide interests.[5] The number of guided modes excited in the fiber and their properties are essential to understand and analyze pulse evolution of these guided modes. A multimode optical fiber enables the propagation of more than one mode and is not restricted to a single wavelength.[6,7] Many approaches have been developed to realize a much high transmission capacity by the higher-order modes in the multi-mode fiber, and various multi-mode fibers that guide two or three LP modes have been proposed for the MDM systems.[8,9]

The challenge of multi-mode fiber usage is mode coupling leading to additional impairments in the signal, and it is also important to analyze the intensity distributions in the fiber output that are affected by the mode dispersion arising from the mode group.[10] Meanwhile, the high-order nonlinearities such as two-photon absorption in the multi-mode fiber could significantly affect the performance of the MDM systems, and thus much attention were paid on their effects in recent years.

Two-photon absorption process has been extensively studied because of the enormous number of technological applications. Specially, as a high-order nonlinear optical process, the imaginary part of the high order nonlinear susceptibility is related to the extent of the two-photon absorption in an optical fiber, and induces serious effects on pulse propagation. If the solitons propagate in a two-mode fiber with the two-photon absorption, then the traveling pulses may experience waveform distortion and frequency shift. Moreover, a dispersive wave radiation may appear in the system and result in the decrease of the transmission capacity. The effects of the two-photon absorption on the soliton evolution cannot be neglected and may be compensated for by the frequency-dependent optical gain in an optical fiber.[11,12] Some exciting progress on the nonlinear pulse propagation in the multi-mode fiber was achieved in recent years, and reminds that MDM can increase the capacity of an optical fiber system over the multi-mode fiber by the useful control.

In this paper, soliton propagation and interaction are numerically investigated in a two-mode fiber with the two-photon absorption, soliton dynamics and the effects of the two-photon absorption are demonstrated in normal and anomalous

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dispersion regimes, and an available control to suppress the effects is proposed by the use of the nonlinear gain with filter.

2. Model

The pulse propagation in a two-mode optical fiber within the weakly coupling regime was investigated and analyzed in some former references, where the mode coupling due to various external factors was weak such as the coupling between LP_{01} and LP_{11} modes. For simplicity, the two-fold degeneracy of the LP_{11} mode (LP_{11a} and LP_{11b}) is not taken into account in this work, and it is assumed that only one of the two degenerate modes is excited in the two-mode fiber, which will not couple to the other degenerate mode because of the ideally isotropic property. Namely, only the LP_{01} and LP_{11a} modes are excited when the nonlinear pulses propagate in such a two-mode fiber.[13,14]

When nonlinear pulses propagate in a two-mode optical fiber with the two-photon absorption under the coupling between the LP_{01} and LP_{11} modes, the corresponding nonlinear coupling Schrödinger equations governing the pulse propagation are given by[13,14]

$$\mathrm{j}\frac{\partial A}{\partial z}-\mathrm{j}\frac{1}{2}d_1\frac{\partial A}{\partial t}-\frac{1}{2}\beta_{2A}\frac{\partial^2 A}{\partial t^2}+\frac{8}{9}\gamma|A|^2A+\frac{4}{3}\gamma f_{AB}|B|^2A+\mathrm{j}\alpha|A|^2A=0, \tag{1}$$

$$\mathrm{j}\frac{\partial B}{\partial z}+d_0B+\mathrm{j}\frac{1}{2}d_1\frac{\partial B}{\partial t}-\frac{1}{2}\beta_{2B}\frac{\partial^2 B}{\partial t^2}+\frac{8}{9}\gamma f_{BB}|B|^2B+\frac{4}{3}\gamma f_{AB}|A|^2B+\mathrm{j}\alpha|B|^2B=0, \tag{2}$$

where A and B are the slowly varying envelopes of the LP_{01} and LP_{11} modes, respectively. z and t are the propagation distance and delayed time, respectively. d_0 is the average propagation constant of the LP_{11} mode in reference to the LP_{01} mode, and d_1 is the differential mode group delay (DMGD) coefficient between the LP_{11} and LP_{01} modes. β_{2A} and β_{2B} are the group velocity dispersion (GVD) coefficients of the LP_{01} and LP_{11} modes, respectively. γ, f_{AB}, and f_{BB} are the nonlinear coupling coefficients between the spatial modes,[13,14] and α is the two-photon absorption coefficient.

To normalize Eqs. (1) and (2), the following relations are introduced:

$$u=\sqrt{\gamma L_{\mathrm{D}}}\times A, \tag{3}$$

$$v=\exp(-\mathrm{j}d_0z)\cdot\sqrt{\gamma L_{\mathrm{D}}}\times B, \tag{4}$$

$$\xi=\frac{z}{L_{\mathrm{D}}},\quad \tau=\frac{t}{T_0},\quad L_{\mathrm{D}}=\frac{T_0^2}{|\beta_{2A}|}, \tag{5}$$

$$D_1=\frac{L_{\mathrm{D}}}{T_0}d_1,\quad \beta_1=\frac{\beta_{2A}}{|\beta_{2A}|},\quad \beta_2=\frac{\beta_{2B}}{|\beta_{2A}|},\quad \rho=\frac{\alpha}{\gamma}, \tag{6}$$

where T_0 is the initial pulse-width, and L_{D} is the dispersion length corresponding to the group velocity dispersion (β_{2A}) of the LP_{01} mode.

Equations (1) and (2) can be normalized into the following two equations:

$$\mathrm{j}\frac{\partial u}{\partial\xi}-\mathrm{j}\frac{1}{2}D_1\frac{\partial u}{\partial\tau}-\frac{1}{2}\beta_1\frac{\partial^2 u}{\partial\tau^2}+\frac{8}{9}|u|^2u+\frac{4}{3}f_{AB}|v|^2u+\mathrm{j}\rho|u|^2u=0, \tag{7}$$

$$\mathrm{j}\frac{\partial v}{\partial\xi}+\mathrm{j}\frac{1}{2}D_1\frac{\partial v}{\partial\tau}-\frac{1}{2}\beta_2\frac{\partial^2 v}{\partial\tau^2}+\frac{8}{9}f_{BB}|v|^2v+\frac{4}{3}f_{AB}|u|^2v+\mathrm{j}\rho|v|^2v=0. \tag{8}$$

Equations (7) and (8) describe the nonlinear pulse propagation in the two-mode optical fiber with the two-photon absorption.

3. Numerical results and analysis

In a real two-mode fiber, the behaves of the normalized slowly varying envelopes propagating in the LP_{01} and LP_{11} modes become inhomogeneous because of nonlinearities, such as the two-photon absorption with high-order nonlinearity. Such behaves can be obtained by the approximate analytical solutions and the numerical simulation analysis through the nonlinear coupling Schrödinger equations (7) and (8),[15,16] which are expected to be in agreement with the experimental results. In this work, the effects induced by the two-photon absorption are investigated by the direct numerical simulation analysis.

For a typical two-mode fiber with normalized frequency V of $2.405 < V < 3.832$, the nonlinear coupling coefficient f_{AB} is calculated in the range of $0.102 < f_{BB} < 0.964$ and the nonlinear coefficient f_{BB} is calculated in the range of $0.168 < f_{AB} < 0.627$. For $T_0 = 1.0$ ps, the normalized DMGD coefficient is in the range of $0 < D_1 < 5.0$. The normalized GVD coefficient of the LP_{01} mode $\beta_1 = 1.0$ represents the normal dispersion, and $\beta_1 = -1.0$ represents the anomalous dispersion. The normalized GVD coefficient of the LP_{11} mode β_2 is essentially the group velocity dispersion ratio of the LP_{11} and LP_{01} modes, and is calculated in the range of $0.9 < \beta_2 = \beta_{2B}/\beta_{2A} < 3.6$.[13,14,17,18]

Effects of the two-photon absorption on the soliton propagation can be investigated by using the split-step Fourier algorithm. The nonlinear coupling coefficients of $f_{BB} = 0.90$, $f_{AB} = 0.60$ and the normalized DMGD coefficient of $D_1 = 2.0$ are used in the following figures. For a typical two-mode fiber, the initial soliton pulse-width of $\tau_0 = 1.0$ (corresponding to the initial pulse-width $T_0 = 1.0$ ps) and the normalized group velocity dispersion of the LP_{01} mode of $\beta_1 = \pm 1.0$ (corresponding to the group velocity dispersion of the LP_{01} mode of $\beta_{2A} = \pm 1.0$ ps^2/km, and the dispersion length $L_{\mathrm{D}} = 1.0$ km) are used in the actual calculation.

Figure 1 is the normalized one-soliton intensity in each mode versus the propagation distance without the two-photon

absorption in normal and anomalous dispersion regimes, and the initially input soliton pulses in the two modes are

$$u(\tau,\xi=0)=v(\tau,\xi=0)=\mathrm{sech}(\tau), \tag{9}$$

where the normalized GVD coefficients of the LP_{01} and LP_{11} modes are selected as $\beta_1=\pm1.0$ and $\beta_2=\pm1.0$ or $\beta_2=\pm1.4$, respectively.

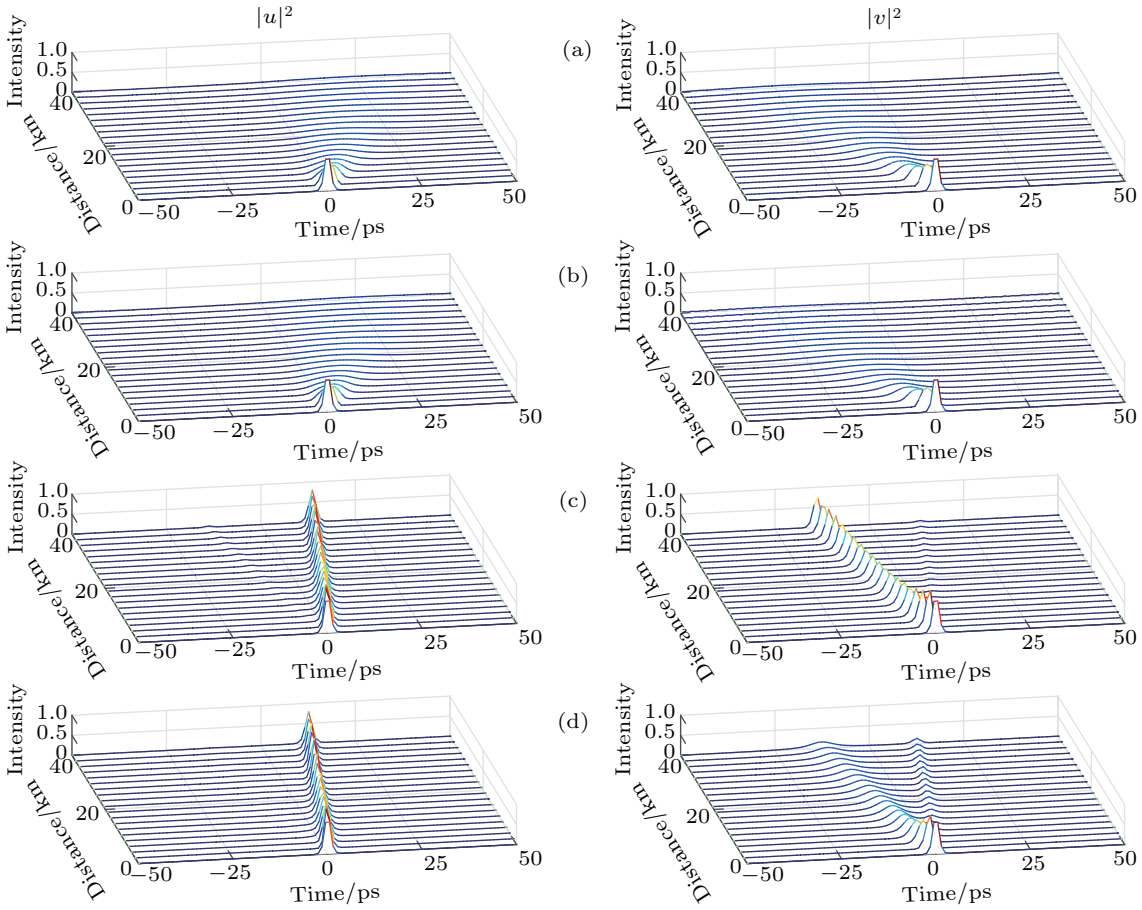


Fig. 1. The normalized one-soliton intensity versus the propagation distance without the two-photon absorption in normal and anomalous dispersion regimes. (a) $\beta_1=1.0$ and $\beta_2=1.0$, (b) $\beta_1=1.0$ and $\beta_2=1.4$, (c) $\beta_1=-1.0$ and $\beta_2=-1.0$, (d) $\beta_1=-1.0$ and $\beta_2=-1.4$.

The numerical calculation results show that the soliton can hardly propagate in the normal dispersion regime ($\beta_1=1.0$, and $\beta_2=1.0$ or $\beta_2=1.4$), and fast collapse within a very short distance in both modes. The solitons can stably propagate in the anomalous dispersion regime for suitable GVDs in two modes (such as $\beta_1=-1.0$ and $\beta_2=-1.0$) without the two-photon absorption, but the soliton becomes unstable and gradually crumbles away in the LP_{11} mode when the absolute value of its GVD coefficient becomes big (such as $\beta_2=-1.4$), and there is obvious time shift induced by the DMGD in the soliton propagation.

Figure 2 is the normalized one-soliton intensity in each mode versus the propagation distance with the two-photon absorption in the anomalous dispersion regime of $\beta_1=-1.0$ and $\beta_2=-1.0$, where the initially input soliton pulses are chosen as Eq. (9), and the different coefficients of the two-photon absorption are selected as $\rho=0.02$, 0.05, 0.15, and 0.25 respectively. We can find when the strength (coefficient) of the two-photon absorption is very small, the soliton can propagate stably for a short distance in each mode. With increase in the two-photon absorption strength (coefficient), the soliton evolves into the broadening pulse with decreasing amplitude until complete collapse. When the strength (coefficient) of the two-photon absorption is large enough, the soliton can hardly propagate, and fast collapse within a very short distance. Furthermore, the soliton has robust features in the LP_{01} mode compared with the soliton in the LP_{11} mode, such as good resistance to soliton disintegration. From the figures above, we can see that the soliton dynamics depend strictly on the sign and magnitude of the GVD coefficient in each mode and the strength (coefficient) of the two-photon absorption in the two-mode fiber. Figure 3 is the effective propagation distance (within the distance soliton can be distinguished from subside band) in each mode versus the two-photon absorption coefficient in the anomalous dispersion regime of $\beta_1=-1.0$ and $\beta_2=-1.0$. The two-photon absorption may lead to the destructive effects, result in waveform distortion and collapse during soliton propagation, and reduce the effective propagation distance.

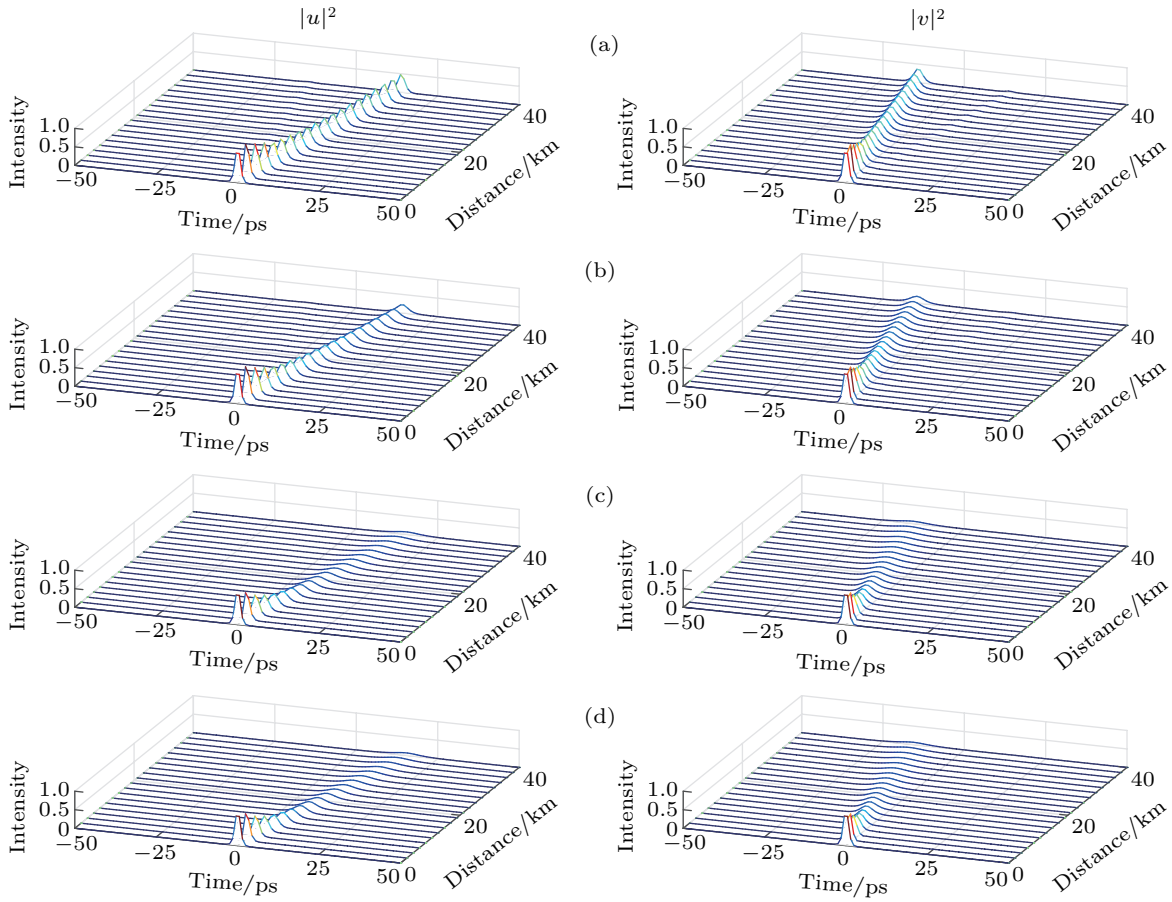


Fig. 2. The normalized one-soliton intensity versus the propagation distance with the two-photon absorption in the anomalous dispersion regime. (a) $\rho = 0.02$, (b) $\rho = 0.05$, (c) $\rho = 0.15$, (d) $\rho = 0.25$.

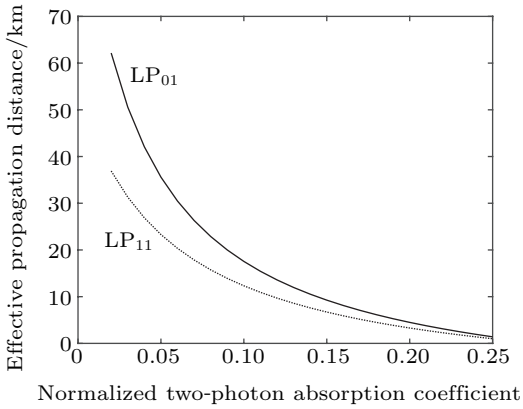


Fig. 3. The effective propagation distance versus the normalized two-photon absorption coefficient in the anomalous dispersion regime.

Figure 4 is the normalized three-soliton intensity in each mode versus the propagation distance without the two-photon absorption in normal and anomalous dispersion regimes ($\beta_1 = \pm 1.0$ and $\beta_2 = \pm 1.0$ or $\beta_2 = \pm 1.4$, respectively). Figure 5 is the normalized three-soliton intensity in each mode versus the propagation distance with the two-photon absorption in the anomalous dispersion regime of $\beta_1 = -1.0$ and $\beta_2 = -1.0$. The initially input three-soliton pulses in the two modes are

$$u(\tau, \xi = 0) = v(\tau, \xi = 0) = \operatorname{sech}(\tau - \Delta) + \operatorname{sech}(\tau) + \operatorname{sech}(\tau + \Delta), \quad (10)$$

where Δ is the delay time separation between two neighboring solitons in the same mode, and $\Delta = 10$ is given in the figures below. The different coefficients of the two-photon absorption are selected as $\rho = 0.02$, 0.05, 0.15, and 0.25.

When the initial separation between neighboring solitons is larger than five times of the full width at half maximum (FWHM) of the soliton in a path-average dispersion transmission system, the interaction can be suppressed effectively.[1,15,16] From Figs. 4 and 5, we can see that the three solitons can hardly propagate in the normal dispersion regimes. In addition, the three solitons can stably propagate a very long distance in the anomalous dispersion regimes for suitable GVD in two modes (such as $\beta_1 = -1.0$ and $\beta_2 = -1.0$) without the two-photon absorption, but the neighboring solitons become unstable and overlap with each other when the absolute value of the GVD coefficient of the LP_{11} mode gets big (such as $\beta_2 = -1.4$). Furthermore, the two-photon absorption enhances the interaction between two neighboring solitons even if the separation ($\Delta = 10$ is about 5.68 times of FWHM of the soliton) is larger than five times of the soliton FWHM. The two-photon absorption may lead to the weighty effects on the interaction of solitons in the LP_{11} mode. There is obvious time shift in soliton propagation because of the DMGD and energy exchange between two modes induced by the two-photon absorption.

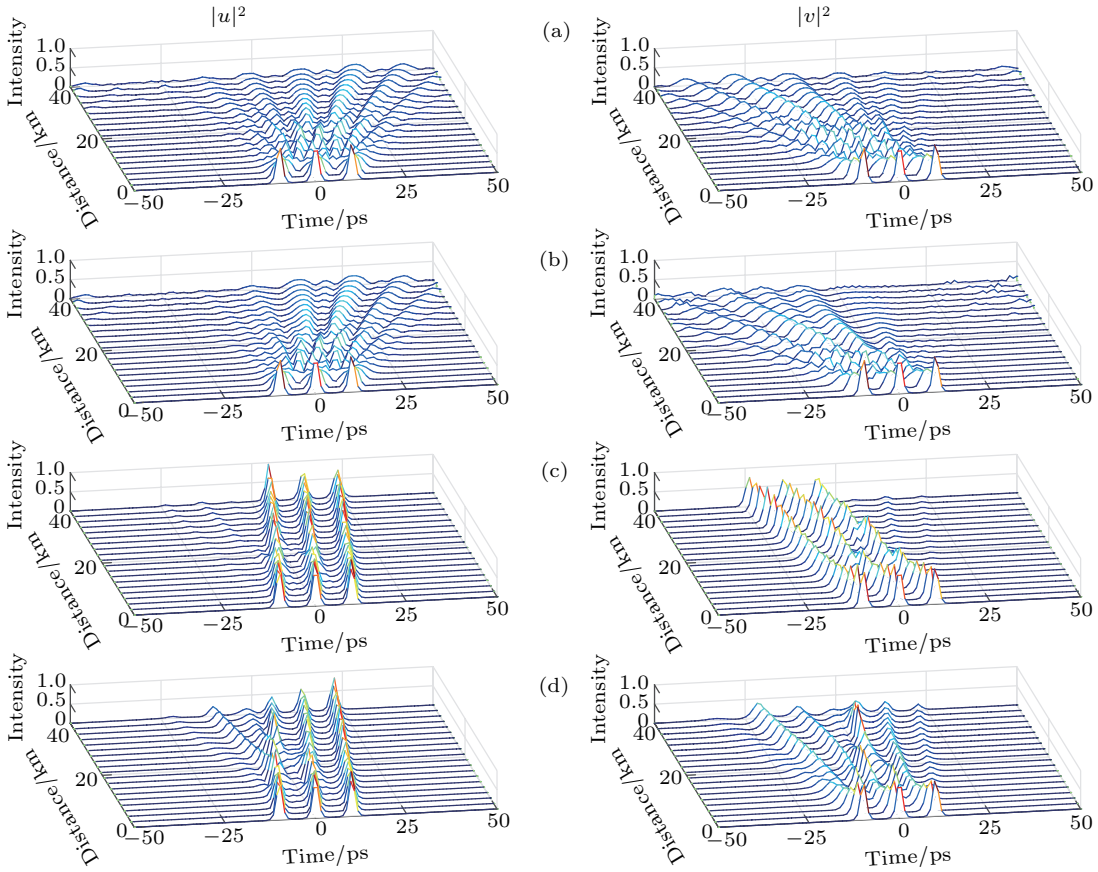


Fig. 4. The normalized three-soliton intensity versus the propagation distance without the two-photon absorption in normal and anomalous dispersion regimes. (a) $\beta_1 = 1.0$ and $\beta_2 = 1.0$, (b) $\beta_1 = 1.0$ and $\beta_2 = 1.4$, (c) $\beta_1 = -1.0$ and $\beta_2 = -1.0$, (d) $\beta_1 = -1.0$ and $\beta_2 = -1.4$.

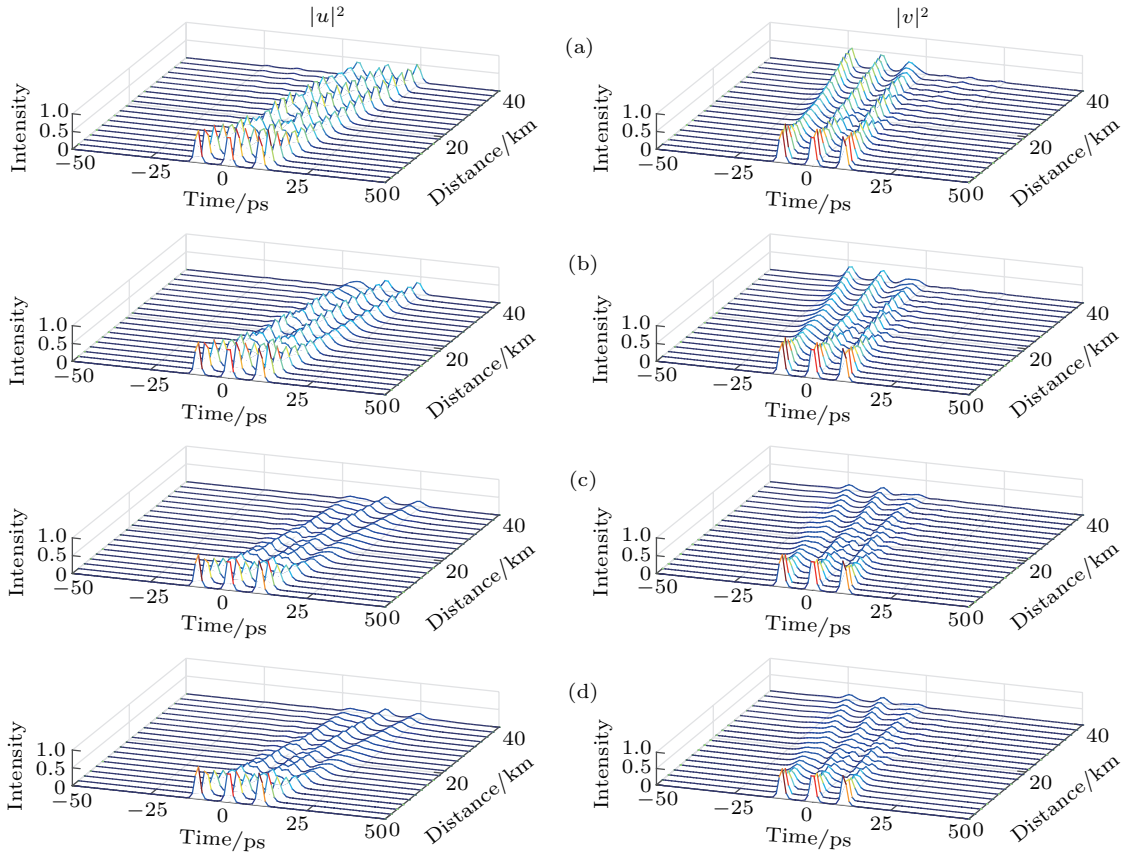


Fig. 5. The normalized three-soliton intensity versus the propagation distance with the two-photon absorption in the anomalous dispersion regime. (a) $\rho = 0.02$, (b) $\rho = 0.05$, (c) $\rho = 0.15$, (d) $\rho = 0.25$.

Figure 6 is the interaction distance in each mode versus the two-photon absorption coefficient in the anomalous dispersion regime of $\beta_1 = -1.0$ and $\beta_2 = -1.0$. The interaction distance, which is defined as the distance where the timing shifts of the neighboring solitons exceed one half of their FWHM,[15,16] depends strictly on the strength (coefficient) of the two-photon absorption and the separation between solitons in each mode.

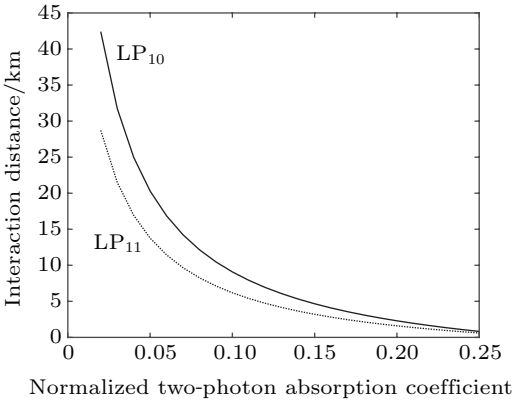


Fig. 6. The interaction distance versus the normalized two-photon absorption coefficient in the anomalous dispersion regime.

The results in figures above show that perturbation induced by the two-photon absorption results in subside band of the soliton pulses, and enhances the soliton interaction. Meantime, the two-photon absorption causes the time relative displacement between the two modes, then the time relative displacement leads to the disintegration of the solitons in each mode, and enhances the interaction between the neighboring solitons. The effective propagation distance and the interaction distance are determined by the strength (coefficient) of the two-photon absorption because of its various destruction on the soliton propagation and interaction.

4. Control of the soliton propagation and interaction

In order to stabilize the soliton propagation and control the soliton interaction resulting from the perturbation effects induced by the two-photon absorption, the nonlinear gain combining with filter is proposed to suppress these effects in the two-mode fiber, and the soliton pulses can be described by the modified nonlinear coupling Schrödinger equations[15,19]

$$\begin{aligned} &\mathrm{j}\frac{\partial u}{\partial \xi} - \mathrm{j}\frac{1}{2}D_1\frac{\partial u}{\partial \tau} - \frac{1}{2}\beta_1\frac{\partial^2 u}{\partial \tau^2} \\ &+\frac{8}{9}|u|^2 u + \frac{4}{3}f_{AB}|v|^2 u + \mathrm{j}\rho|u|^2 u \\ &= \mathrm{j}\sigma_1 u + \mathrm{j}\sigma_2|u|^2 u + \mathrm{j}\sigma_3|u|^4 u + \mathrm{j}\eta\frac{\partial^2 u}{\partial \tau^2}, \end{aligned} \tag{11}$$

$$\begin{aligned} &\mathrm{j}\frac{\partial v}{\partial \xi} + \mathrm{j}\frac{1}{2}D_1\frac{\partial v}{\partial \tau} - \frac{1}{2}\beta_2\frac{\partial^2 v}{\partial \tau^2} \\ &+\frac{8}{9}f_{BB}|v|^2 v + \frac{4}{3}f_{AB}|u|^2 v + \mathrm{j}\rho|v|^2 v \\ &= \mathrm{j}\sigma_1 v + \mathrm{j}\sigma_2|v|^2 v + \mathrm{j}\sigma_3|v|^4 v + \mathrm{j}\eta\frac{\partial^2 v}{\partial \tau^2}, \end{aligned} \tag{12}$$

where σ_1, σ_2, and σ_3 are the coefficients of the linear gain, the nonlinear gain, and the nonlinear gain saturation, respectively, and η is the coefficient of the filter. These coefficients are selected under the condition[15,19]

$$\sigma_1 < 0, \quad \sigma_3 < 0, \quad \eta < 2(\sigma_2 - \rho), \tag{13}$$

$$15\sigma_1 - 5[\eta - 2(\sigma_2 - \rho)] + 8\sigma_3 = 0. \tag{14}$$

Figures 7 and 8 demonstrate the normalized one-soliton intensity and three-soliton intensity versus the propagation distance with the controllable nonlinear gain and the filter. The coefficient of the two-photon absorption is selected as $\rho = 0.25$ in order to show the control effect of the nonlinear gain and the filter. The coefficients of the linear gain, the nonlinear gain, the nonlinear gain saturation, and the filter are $\sigma_1 = -0.03$, $\sigma_2 = 0.55$, $\sigma_3 = -0.20$, and $\eta = 0.18$. The normalized GVD coefficients of the LP_{01} and the LP_{11} modes are chosen as $\beta_1 = -1.0$ and $\beta_2 = -1.0$ or $\beta_2 = -1.4$, respectively.

It is shown that the nonlinear gain control can stabilize the soliton propagation, reduce the energy exchange between the two modes, and control the neighboring soliton interaction in each mode even if the strength (coefficient) of the two-photon absorption is large enough (such as $\rho = 0.25$) and the absolute value of the GVD coefficient of the LP_{11} mode is big enough (such as $\beta_2 = -1.4$). The results mean that the soliton properties (such as shape, height, width) and soliton separation required for the soliton communication are recovered, and the interaction between solitons in the same mode or the energy exchange between the two modes is suppressed when there is an available control of the nonlinear gain with filter in the transmission line. The reason is that the nonlinear gain can suppress the linear wave growth due to the excess gain during soliton propagation, and the narrow-band filter can suppress the frequency shift. Combined with the narrow-band filter, the nonlinear gain with high-order terms perfectly amplifies the soliton with the large amplitudes while the linear wave with the small amplitudes is not amplified.[15,16,19] These results show that mode division multiplexing can increase the capacity of an optical fiber system over the multimode fiber by the available control, where modes are selectively excited in the fiber with MDM channels (such as the LP_{01} and LP_{11} modes in a two-mode fiber).

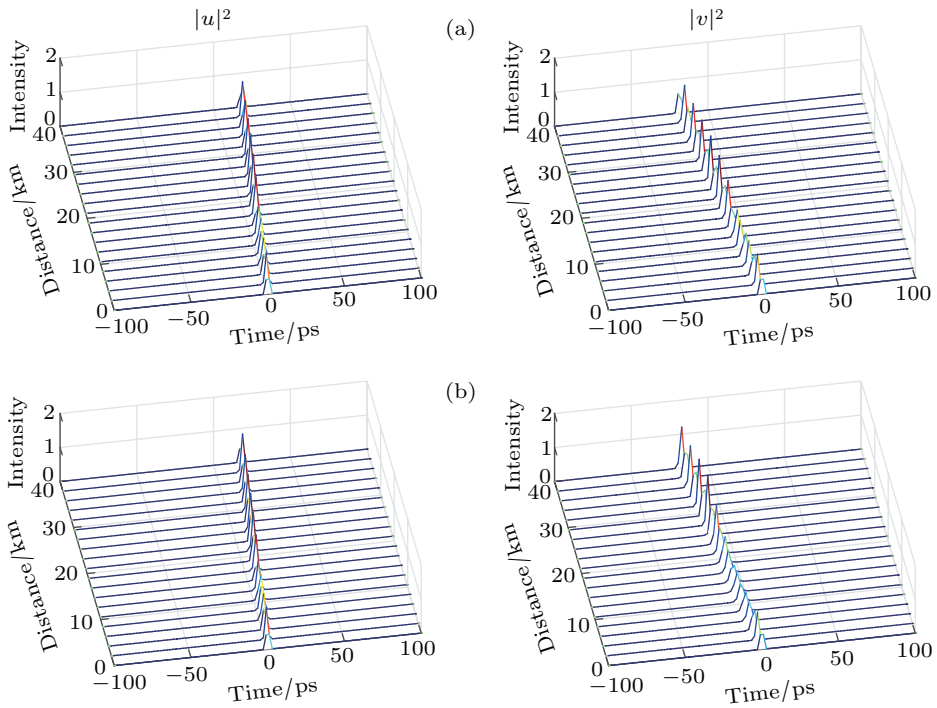


Fig. 7. The normalized one-soliton intensity versus the propagation distance with controllable nonlinear gain and filter. (a) $\beta_1 = -1.0$ and $\beta_2 = -1.0$, (b) $\beta_1 = -1.0$ and $\beta_2 = -1.4$.

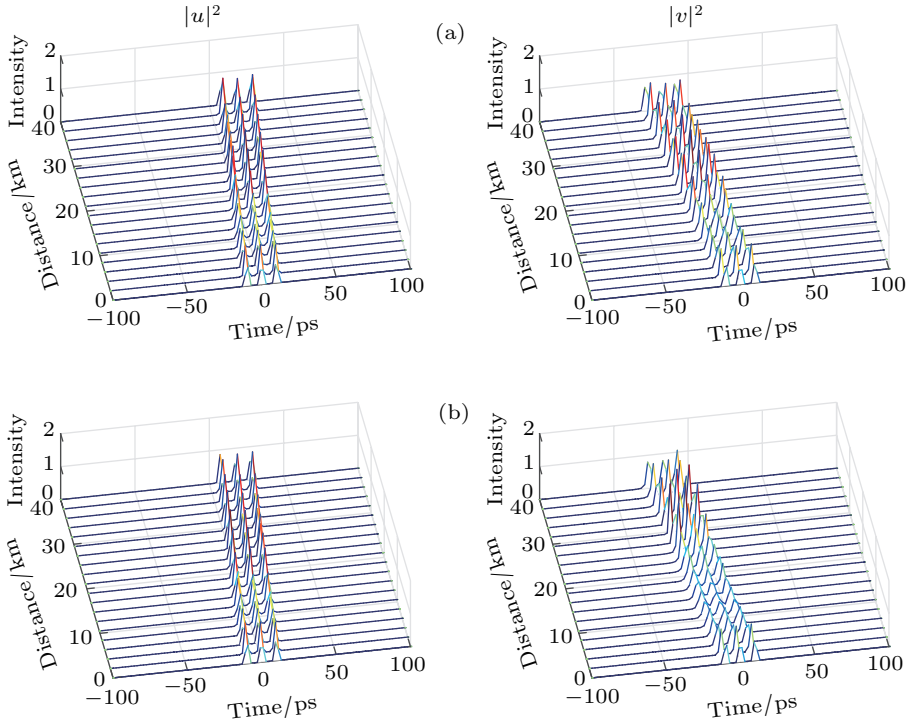


Fig. 8. The normalized three-soliton intensity versus the propagation distance with controllable nonlinear gain and filter. (a) $\beta_1 = -1.0$ and $\beta_2 = -1.0$, (b) $\beta_1 = -1.0$ and $\beta_2 = -1.4$.

5. Conclusion

Soliton evolution is numerically investigated in a two-mode fiber with the two-photon absorption, and the effects of the two-photon absorption on the soliton propagation and interaction are demonstrated in different dispersion regimes. Soliton dynamics depend strictly on the sign and magnitude of the GVD coefficient of each mode and the strength (coefficient) of the two-photon absorption. The two-photon absorption leads to the soliton collapse, enhances the neighboring soliton interaction in the two modes, and increases the energy exchange between the two modes. The solitons may have robust features in the LP_{01} mode compared with those in LP_{11} in the presence of the two-photon absorption, such as resistance to waveform distortion and neighboring soliton interaction. Fi-

nally, the available control is proposed to suppress the effects by nonlinear gain with filter, and the results show that the soliton properties (such as shape, height, width) and soliton separation required for the soliton communication are recovered, and the soliton interaction in the same mode or the energy exchange between the two modes is effectively suppressed.

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